A New 77 GHz Automotive Phase Coded CW Multi-port Radar Sensor Architecture

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Abstract— **A new, low-cost architecture of a 77 GHz automotive phase coded continuous wave radar sensor is proposed to provide accurate velocity and range measurements. Orthogonal signals provided by the multi-port module are combined into an intrinsic Doppler rejection technique, enabling accurate pulse compression. An increased range resolution is achieved using the pulse compression technique, while CW mode provides increased system solving capability in Doppler domain. The proposed system is an attractive solution for short-range millimeter-wave automotive sensors.**

I. INTRODUCTION

The increasing automobile traffic combined with the complexity of the modern urban environment enable the development of new safety measures to avoid car crashing. The automotive safety researchers have been looking for a long time to improve traffic conditions and security; seat belts, air bags, car frames, and bodies that protect the people inside have been successfully implemented.

The advances in microwave and microelectronic techniques mark a change in the automotive safety industry philosophy: from safety systems that react in very short time after an accident occurs, minimizing injuries and damage, to those that prevent collisions altogether [1]. The optimal solution will assist the driver in order to avoid collisions. Such systems may be, but are not limited to, the adaptive cruise control (ACC) and the forward-looking collision warning systems (CWS). These systems make use of sensors to collect information about the traffic and obstacles in the roadway ahead. In ACC systems, provided information is used to automatically maintain a fixed headway or a constant distance (speed) between vehicles; as for CWS, the information is used to warn the driver about potentially hazardous situations.

As the radar sensor is the key element for both systems discussed above, the development of such systems is of great interest. The frequency allocation, almost all over the world, tends to favor the use of the 76 - 77 GHz millimeter-wave band for automotive radar applications. The use of this frequency makes further miniaturization possible, in order to meet the stringent size requirements formulated by automakers. The operating frequency of 77 GHz is located in a lower attenuation region, enabling a higher detection range.

The un-modulated CW radar has great velocity detection capabilities through the measurement of the Doppler frequency but is incapable of measuring the range itself. It was recognized that, by some sort of coding, a CW radar could measure the range as well [2], [3]. Reliable results were achieved by coding the frequency (FMCW radar) or the phase (PCCW radar) [4].

Phase coded (PC) waveforms differ from FM waveforms in that the transmitted pulse is subdivided into a number of equal duration sub-pulses. The phase of each sub-pulse is chosen according to an optimal binary code sequence. An optimal binary code consists of a sequence of +1s and -1s (i.e. the phase alternates between 0^o and 180^o), and it has some remarkable features. Firstly, the peak sidelobe of the autocorrelation function is the minimum possible for a given sequence length and secondly, the compression ratio is equal to the number of elements of the code [2], [3]. Thus, upon reception, the compressed pulse obtained through the correlation will enable the range to target evaluation. Phase coded waveform is sensitive to the Doppler effect, hence, for a large Doppler spread spectrum, compensation is a must.

The proposed architecture effectively rejects the Doppler frequency from the range channel, before the correlation takes place, providing an accurate pulse compression.

II. RADAR SENSOR ARCHITECTURE

The schematic block of the proposed architecture is shown in Fig. 1. In order to increase the legibility of the IF and baseband schematic, amplifying stages were omitted.

The phase of the IF signal, generated by the local oscillator LO_{IF}, is modulated by the sequence given by the optimal code generator (OCG). The resulting signal is further up-converted to 77 GHz and transmitted using a high-gain transmission antenna A_{Tx}. After reflection, the echo signal is received (A_{Rx}), amplified (LNA) and down-converted (MPM) to IF frequency.

The multi-port module (MPM) as described in [5]–[7], is basically a low-cost, low-power consumption, millimeter-wave quadrature down-converter. This module is an additive mixer in which the resulting sum of the millimeter-wave signals is nonlinearly processed using millimeter-wave power detectors.

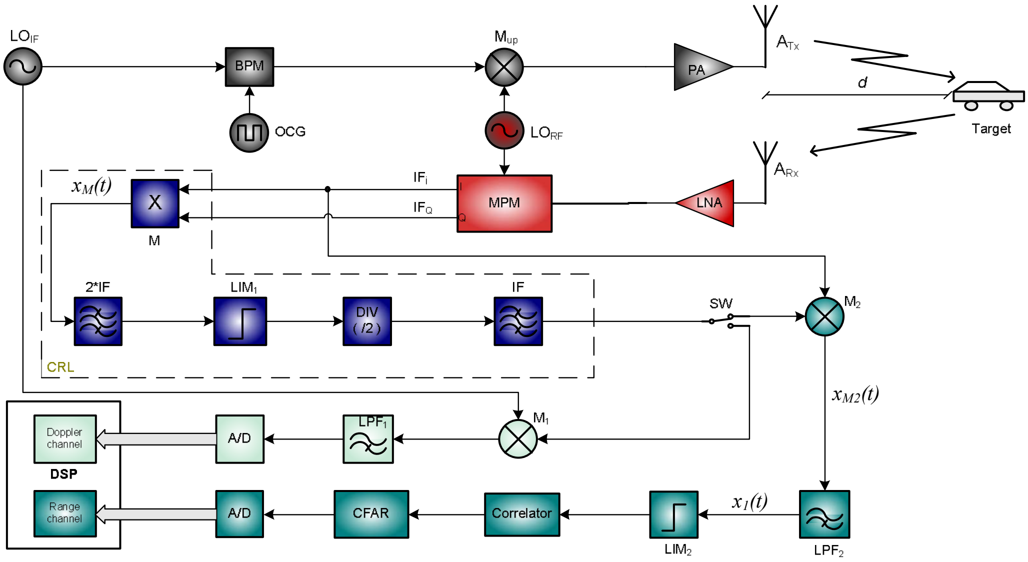

Fig. 1 Schematic block diagram of the proposed automotive PCCW radar architecture

The output signals of the MPM can be expressed using the harmonic representation as follows:

$$x_{IF}^{i}(t) = K(d)\cdot C(t)\cdot \sin[(\omega_{IF} \pm \omega_D)t + \varphi_0] \tag{1}$$

$$x_{IF}^{q}(t) = K(d)\cdot C(t)\cdot \cos[(\omega_{IF} \pm \omega_D)t + \varphi_0] \tag{2}$$

where $C(t)$ is the binary phase coding signal, $K(d)$ is a coefficient accounting for free space propagation losses; ω_D, ω_{IF} are the Doppler, and the IF angular frequency, respectively, and φ_0 is an arbitrary constant phase. The $x^{i}_{IF}(t)$ and $x^{q}_{IF}(t)$ are mixed by M and the output signal of this mixer is given by (3):

$$x_M(t) = 0.5\cdot K_M\cdot[K(d)]^2\cdot\sin\{2[(\omega_{IF}\pm\omega_D)t+\phi_0]\} \tag{3}$$

where K_M is the transfer coefficient of M.

Further, by filtering the signal $x_M(t)$ and by dividing it by 2, we obtain the IF coherent signal used to extract the baseband modulation signal (the optimal code). The output signal of the M_2 mixer is given by equation (4):

$$x_{M_2}(t) = K\cdot C(t)\cdot\{1\pm\cos[2(\omega t+\phi_0)]\} \tag{4}$$

where $K = 0.25\cdot K_{M_2}\cdot[K(d)]^2\cdot K_{CRL}$ and $\omega = \omega_{IF} \pm \omega_D$

The low pass filter LPF_2 is responsible for the selection of the baseband signal, i.e.:

$$x_1(t) = K\cdot C(t) \tag{5}$$

The analog carrier recovery loop (CRL) described in [8], was adapted for I/Q signals, enabling a synchronous demodulation, as long as the instability of the RF local oscillator (LO_{RF}) is negligible over the period between emission and reception (small-range radars).

Let us consider the signal $x_2(t)$ given by the following equation:

$$x_2(t) = K\cdot C(t)\cdot\cos[2(\omega t+\phi_0)] \tag{6}$$

The choice of the IF frequency must be done avoiding the spectral superposition of $X_1(\omega)$ and $X_2(\omega)$. Hence, the following condition must be satisfied:

$$2\omega_{IF} > B_{X_1(\omega)} \tag{7}$$

where $B_{X1(\omega)}$ is the spectral bandwidth $X_1(\omega)$. After correlation the compressed pulse is digitized and sent to the DSP unit (range channel) for further processing. The compression ratio is equal to the number of sub-pulses of the waveform.

Constant false alarm rate (CFAR) implementation is a key factor in the achievement of high range resolution, which, will be ultimately limited by the sub-pulse rise time.

An independent Doppler channel is employed for the measurement of the target velocity. The CRL output signal, Doppler dependent, is down-converted using a coherent signal from the IF local oscillator (LO_{IF}). Afterwards, the Doppler spectrum is selected using LPF_1. The vectorial sum of IF_I and IF_Q yields a phasor characterized by magnitude, angular frequency ω_D and sense of rotation. The Doppler frequency sign is given by the rotation sense of this phasor.

To preserve the simplicity of this system, for multi-target processing, the separation of the targets relies on the spatial selectivity of the antenna. A narrow-beam scanning antenna array is strongly recommended for measurements in multi-target environment. The use of a programmable correlator [9] will make possible the pseudorandom use of optimal codes of constant length, in order to increase the electromagnetic compatibility with other similar devices, and considerably reduce the false alarm rate [2], [3]. The correlator is a physical implementation of a matched-filter; therefore, the signal-to-noise ratio, SNR, is maximized [10]. In addition, the use of longer optimal codes will expand the range detection capability of the millimeter-wave radar sensor.

III. SIMULATION RESULTS

Simulations of the proposed PCCW automotive radar system are performed using the 2006 Advanced Design Software (ADS) of Agilent Technologies. The simulation schematic completes that of Fig. 1 by adding the IF and baseband amplifier stages. The level of transmitted power is 10 dBm, and the gain of the two identical antennas is 10 dBi. In simulations, the carrier frequency (LO_{RF}) and the IF frequency (LO_{IF}) are set to 76 GHz and 750 MHz, respectively. A 7-bit Barker code with 20 ns sub-pulse width drives binary phase modulator (BPM) with a periodicity of 1.4 µs. The MPM computer model, as described in [7], is modified for a central frequency of 77 GHz. The band-pass and low-pass filters are synthesized using ADS Chebyshev analog filter models with 1dB ripple and 30 dB attenuation in the stop band. The gain of the low noise amplifier (LNA) is 15 dB. IF and baseband stage amplifiers have a gain of 25 dB and 30 dB, respectively. The target has a radar cross section (RCS) of 1 m^2 and is placed at 15 m from the emission point.

Initially, simulations are performed assuming stable oscillators (LO_{RF}, LO_{IF}) and no Doppler effect. For the second set of simulations, a Doppler shift of 100 KHz is considered. This is the equivalent of a target that has a speed of around 700 Km/h, when a carrier of 77 GHz is considered.

Figs. 2 and 3 show the baseband spectrum of the echo signal without and with Doppler effect. The bandwidth of this spectrum is around 500 MHz; therefore, condition (7) is always satisfied, when IF is greater than 250 MHz.

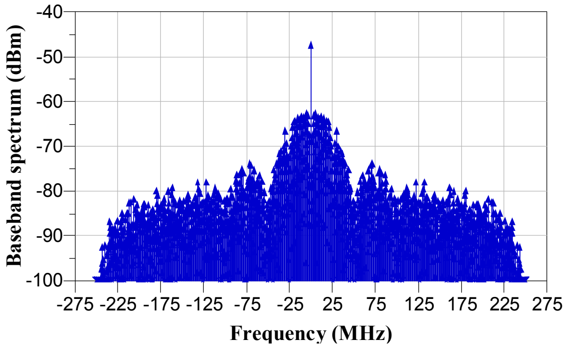

Fig. 2 Baseband spectrum of received signal (7-bit Barker code), f_D = 0 Hz

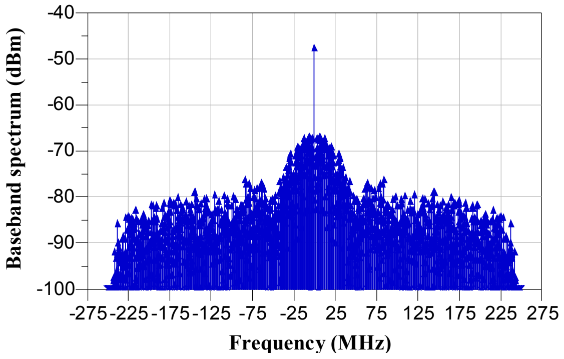

Fig. 3 Baseband spectrum of received signal (7-bit Barker code), f_D = 100 KHz

While no fundamental spectrum changes are observed in the frequency domain, in time domain, because of Doppler shift on Q channel, the second echo signal is lost (see the lower waveform in Fig. 4 and Fig. 5).

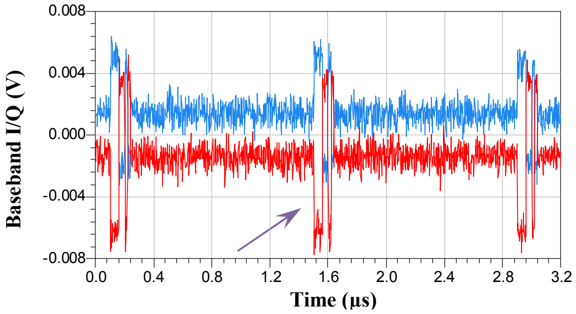

Fig. 4 Baseband I/Q signals at the output of MPM, f_D = 0 Hz

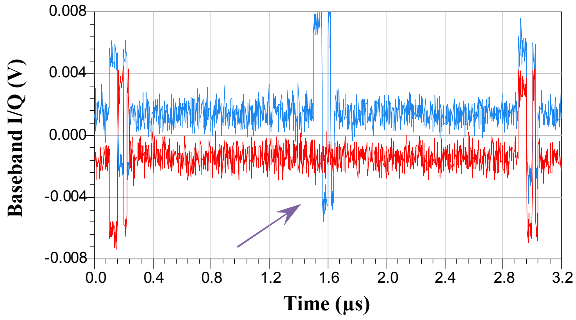

Fig. 5 Baseband I/Q signals at the output of MPM, f_D = 100 KHz

However, after Doppler shift rejection, the signal is completely recovered at the input of the correlator, as shown in Fig. 6. The two way travel time, τ, may be identified in Fig. 6 as being the interval between the beginning of emission (t = 0) and the rise of first sub-pulse echo.

The correlator with fixed reference [3] is implemented using analog delay lines. The correlator output signal is a compressed pulse of ratio 7, as shown in Fig. 7.

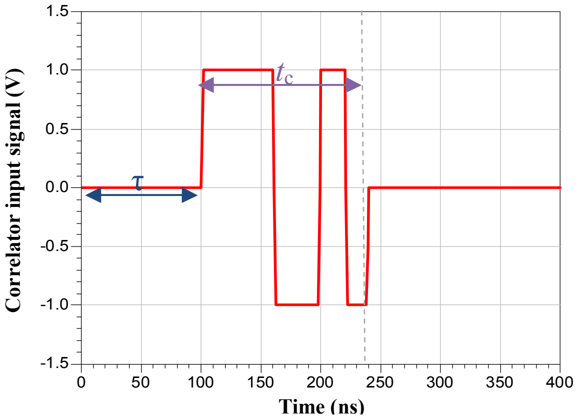

Fig. 6 Demodulated 7-bit Barker code at the input of the correlator

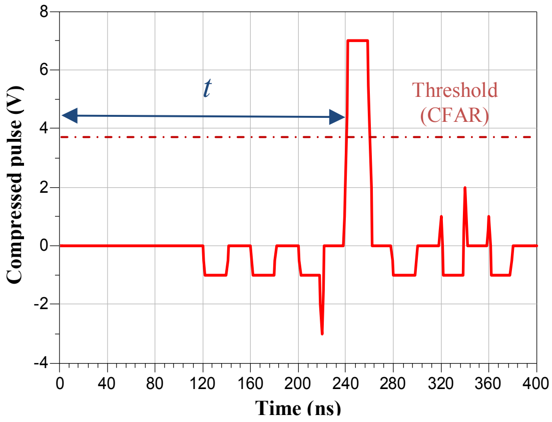

Fig. 7 Pulse compression and range information

The range extraction algorithm, in its basic form, follows the equations below:

$$t = \tau + t_c \tag{9}$$

$$\tau = \frac{2d}{c} \tag{10}$$

where t_c is the correlation time, numerically equal to the pulse code length i.e. t_c = 140 ns (Fig. 6); t is the interval between the beginning of emission (t = 0) and the rise of the main lobe of the compressed pulse as shown in Fig. 7, d is the distance to target, and c is the free space light speed.

Replacing τ from (10) in (9) and solving for d, we obtain:

$$d = \frac{c}{2}\left(t - t_c\right) \tag{11}$$

In our case, t is found to be 240 ns, and from (11) we obtain d = 15 m, which is the same value as the one set in the ADS simulation. The "reading" error of time t, and so, the accuracy of the detected range, strongly depend on the sub-pulse rise time and the threshold generated by the CFAR module. In this simulation, the rise time of the main lobe is around 4 ns. Thus, a middle level threshold yields a maximum time error of 2 ns, which corresponds to a 0.3 m range detection error.

Doppler information is filtered by LPF_1 after synchronous down-conversion (M_2) and, as seen in Fig. 8, the dominant Doppler frequency is f_D = 100 KHz.

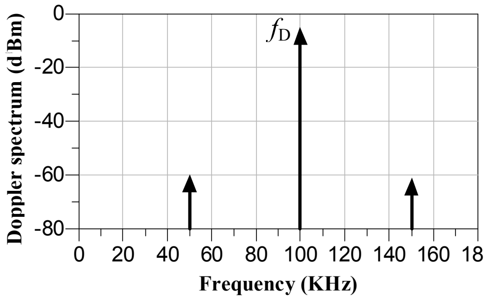

Fig. 8 Doppler spectrum at the input of A/D module

The real world automotive targets generate smaller Doppler deviation (1 KHz – 35 KHz), therefore, the range channel exhibits a total immunity to Doppler effect. The result above has been obtained assuming a stable LO.

In order to estimate the influence of the LO instability over the detected Doppler, we have to evaluate the LO short-term frequency drift. In normal operating conditions, the LO is exposed to the ambient temperature changes, and, as a consequence, the frequency will shift from its nominal value. The typical stability for a 77 GHz Gunn oscillator is found to be 3 MHz/°C [11]. Spearfish, South Dakota, holds the world record for the fastest temperature change i.e. 27 °C/120 s in January 1943. Assuming a target situated at 30 m, the two ways propagation time is 0.1 µs. In this case, the maximum LO frequency drift due to temperature is equal to 0.0675 Hz. This result shows that typical LO frequency instability has negligible influence over target velocity estimation for small range CW radars.

IV. CONCLUSIONS

A new 77 GHz automotive PCCW multi-port radar architecture has been presented in this paper. The compression of the optimal phase code signal was shown to be useful for accurate range detection. This is possible because of Doppler frequency rejection before the correlation process. The CW was shown to be useful for the accurate measurement of target velocity. The performed simulations successfully proved the capabilities of the proposed architecture, enabling the design of compact, low-cost millimeter-wave automotive radars.

ACKNOWLEDGMENT

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REFERENCES

[1] W.D. Jones, "Keeping Cars from Crashing," *IEEE Spectrum*, vol. 30, pp. 40–45, September 2001.

[2] M.I. Skolnic, *Introduction to radar systems*, 3rd ed., McGrow-Hill, 2001.

[3] M.I. Skolnic, *Radar Handbook*, 2nd ed., McGrow-Hill, 1990.

[4] J.K. Christiensen, M.J. Underhill, "Phase coded pulse Doppler and continuous wave 77 GHz radar measurement and analysis facility", *IEE Proceedings on Radar Sonar Navig*ation, vol. 151, pp. 365-374, Dec. 2004.

[5] E. Moldovan, R. G. Bosisio, Ke Wu, "A New 94-GHz Six-Port Collision-Avoidance Radar Sensor," *IEEE Transaction on Microwave Theory and Techniques,* vol. 52, pp. 751-759, March 2004.

[6] E. Moldovan, R. G. Bosisio, Ke Wu, "W-Band Multiport Substrate-Integrated Waveguide Circuits," *IEEE Transaction on Microwave Theory and Techniques,* vol. 54, pp. 625-632, February 2006.

[7] S.O. Tatu, E. Moldovan, "V-band Multi-port Heterodyne Receiver for High-speed Communication Systems", *EURASIP Journal on Wireless Comm. and Networking*, vol. 2007, Article ID 34358, 7 pages, 2007.

[8] D.M. Pozar, *Microwave and RF Design of Wireless Systems*, John Wiley and Sons, New York, 2001.

[9] Robert W. Brocato, "Programmable SAW Development," Sandia National Laboratories, Albuquerque, CA, Rep. SAND2004-5255, 2004

[10] George L. Turin, "An introduction to matched filters", *IEEE Proceedings*, vol. 64, no. 7, pp. 1092-1112, July 1976.

[11] Millimeter-wave Oscillator Design, Application Note [Online]. Available: http://www.mdtcorp.com/prodfiles/MDT%20Gunn%20oscillator%20design%20applications.pdf.